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Purification of Eutrophic Water by Five Aqua-Cultured Plants in Lake Hongfeng, Guiyang, China

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Abstract: The purification efficiency of eutrophic water by five aqua-cultured plants (*Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, *Alternanthera philoxeroides*) in Lake Hongfeng, China, was investigated. The results indicated that the biomass of *Myriophyllum verticillatum* and *Alternanthera philoxeroides* reached the highest level in 87 days after transplant. The removal efficiencies of total nitrate (TN), total phosphorus (TP), chemical oxygen demand (COD_{Cr}), and chlorophyll (*Chl-a*) by the plants ranged from 44% to 96%. The Secchi depth (SD) increased from 0.08-0.1 m to 1.3-3.2 m for the experiments with five cultivars of aqua-cultured plants. Purification efficiency of eutrophic water correlated significantly, in a positive way, with biomass amount and plant productivity. The Carlson's trophic state indexes decreased from 76 to 21 when the cultivar was *Myriophyllum verticillatum*, suggesting that *Myriophyllum verticillatum* can be selected as the plant to remediate karst drainage areas of Guizhou Plateau, where the water body underwent eutrophication. The research results provided a good case for lake environmental management and recovery in karst areas of Yunnan-Guizhou Plateau, China.

Key words: aqua-cultured plants; eutrophic water; Lake Hongfeng; remediation; Carlson's trophic state index

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0 Introduction

Lake-eutrophication, a critical global environmental issue, has played a major role in numbers of serious disasters[1-4]. In China, more than 66% of lakes have become eutrophic[5, 6]. Lake Hongfeng, an important potable water source in Guiyang, is also facing the same problem[5-7]. Given the eutrophic state of Lake Hongfeng[8], we must take action to protect the quality of water source and ensure the security of drinking water in Guiyang.

Generally, there are many ways such as ecological floating beds and constructed wetlands which are used to purify the eutrophic water through utilization of aquatic plants[2,9-13]. However, the application of constructed wetlands is limited because constructed wetlands cover a large area of land and it is difficult to construct wetlands in the karst drainage area of Guizhou Plateau. Therefore, the ecological floating bed system can be an alternative option[14]. Aquatic macrophytes have been widely applied in floating beds to remediate the eutrophic water. The aboveground biomass could be harvested to remove the nutrients from eutrophic water ultimately[15-17]. Also, the underwater system can create favorable conditions for microbial decomposition of nutrients[18].

Lake Hongfeng, a typical aquatic environment in karst drainage basins, presents a repeated state of eutrophy because the nutriments rise in the water column as a result of carbonate dissolution[5-7]. The status of water quality in the same areas of Lake Hongfeng is worse than Grade V[19]. There are some ways, such as phytoplankton population regulation by eco-remediation, as well as reducing industrial sewage discharge and agricultural non-point source pollution, that were performed for controlling eutrophication[20]. However, the effects of those pathways are not significant. Ecological floating beds may be able to reduce the nutrients in Lake Hongfeng and obtain better effects. At present, it is unclear whether the floating beds can be utilized for ecological restoration. Also, the purification efficiency of *Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, and *Alternanthera philoxeroides* on Lake Hongfeng is unclear. Therefore, the primary objective of the present study is to test the purification efficiency of the five aqua-cultured plants in ecological floating beds. In addition, the purification efficiency is evaluated by utilizing modified Carlson's trophic state index. The results can provide a reference for the management and recovery of lake water environment in Guizhou province, China.

1 Experimental

1.1 Location of Pilot Scale Experiment

Lake Hongfeng, an important drinking water source for over 3 million people in Guiyang, was selected as the study area (Fig. 1). It is located at 31 km west of Guiyang City, Guizhou Province, southwestern China, which is 57.2 km^2 in area and 6.01×10^8 m^3 in storage capacity. It is a heavily polluted seasonal anoxic lake because a large volume of untreated wastewater is discharged into the lake[8]. With the lake being eutrophic, any slight deterioration of water may cause serious social and environmental problems[5-7]. Floating beds were employed to improve the quality of the water. The research was conducted from 1 June to 27 August, 2017 in a lake-bay, where the water body was seriously polluted.

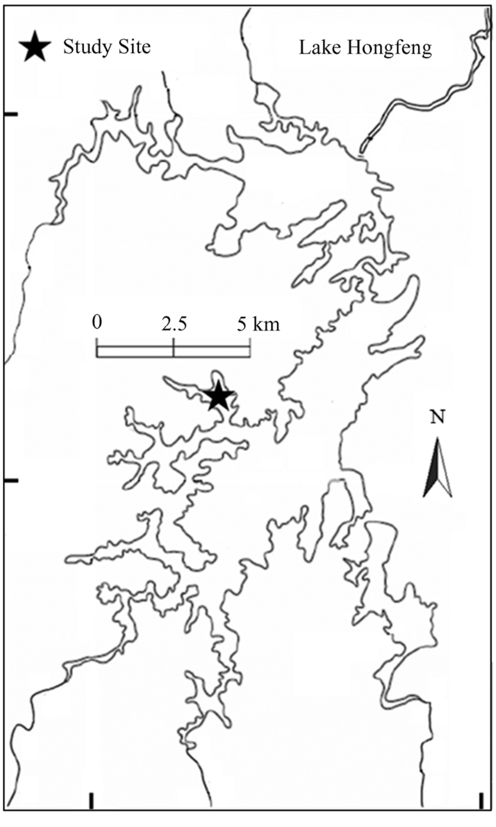

Fig. 1 Study site

1.2 Construction of Pilot Scale Experiment

The enclosure (30 m^2 in area and 5.0 m in water depth) was made of plastic coated polyethylene woven cloth with a frame composed of bamboo poles to test the effects of remediation by floating beds. The framework of each planted floating bed was cultured within the enclosure. It was made of perforated polypropylene foam and fixed by bamboo with the size of 100 cm × 200 cm× 3.5 cm (width × length × height). The size of the hole was 3 cm in diameter, and the interval of each hole was 15 cm. Sieve-style plastic baskets were fixed into the holes by tieline buckles. The roots of plants can grow into water through sieve pores. Five cultivars of aqua-cultured plants, *Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, and *Alternanthera philoxeroides* were selected as test plants. Untreated urban sewage was discharged into the enclosure, which increased the level of eutrophication, when floating beds were constructed. Next, two or three individual plants with the same weight were transplanted into each basket, and then the floating beds were kept into reservoir bay. The control experiments also conducted these steps but with no plants.

1.3 Water Quality Analysis

Approximately 1 L of water samples were taken at 0.5 m below the surface of the water, poured into a cleaned polyethylene bottle, and kept in a dark and cool container. These samples were then transported to the lab for water quality index determination, including total nitrate (TN), total phosphorus (TP), chemical oxygen demand (COD_{Cr}), and chlorophyll (*Chl-a*) which were followed by standard methods[17,18,21,22]. Secchi depth (SD), the transparency of the water, was measured by a black-and-white disk with the diameter of 30 cm. The maximum depth at which the disk can be seen when lowered into the water was marked and measured. All experiments were conducted in triplicates.

2 Result and Analysis

2.1 Growth Characteristics of Floating Bed Plants

The biomass amount and plant productivity of the five cultivars were different under the same conditions (Table 1). The growth rates of fresh weight were calculated to be 1.44, 0.15, 0.17, 2.44, and 1.53 $g \cdot d^{-1}$ for *Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, and *Alternanthera philoxeroides*, respectively. The growth rate of root length showed an order of *Myriophyllum verticillatum* (0.54 $cm \cdot d^{-1}$) > *Chlorophytum comosum* (0.3 $cm \cdot d^{-1}$) > *Alternanthera philoxeroides* (0.22 $cm \cdot d^{-1}$) > *Salix babylonica* (0.07 $cm \cdot d^{-1}$) > *Dracaena sanderiana* (0.03 $cm \cdot d^{-1}$). The fastest growth rate of plant height was *Myriophyllum verticillatum* (0.80 $cm \cdot d^{-1}$), followed by *Alternanthera philoxeroides* (0.45 $cm \cdot d^{-1}$), *Chlorophytum comosum* (0.40 $cm \cdot d^{-1}$), *Salix babylonica* (0.13 $cm \cdot d^{-1}$), and *Dracaena sanderiana* (0.11 $cm \cdot d^{-1}$).

Table 1 Growth indexes of five aqua-cultured plants

Cultivars	Time /d	Fresh weight/g	Root length/cm	Plant height/cm
Chlorophytum comosum	0	5.7 ± 0.19	3.5 ± 0.14	6.6 ± 0.22
	7	22.3 ± 1.3	4.2 ± 0.15	8.4 ± 0.32
	17	74.4 ± 2.7	15.6 ± 0.51	29.7 ± 1.1
	32	86.8 ± 3.3	21.3 ± 0.79	34.9 ± 0.95
	52	102 ± 3.2	24.9 ± 0.77	37.3 ± 1.2
	87	131 ± 4.6	29.7 ± 0.9	41.5 ± 1.1
Salix babylonica	0	19.4 ± 0.44	2.5 ± 0.12	10.0 ± 0.47
	7	20.3 ± 0.62	3.2 ± 0.16	11.3 ± 0.37
	17	23.5 ± 0.59	4.7 ± 0.13	15.2 ± 0.39
	32	27.6 ± 0.97	5.9 ± 0.19	17.4 ± 0.56
	52	30.6 ± 0.88	7.4 ± 0.25	19.8 ± 0.72
	87	32.3 ± 0.73	8.6 ± 0.26	21.5 ± 0.77
Dracaena sanderiana	0	26.9 ± 0.83	5.6 ± 0.18	18.4 ± 0.49
	7	27.4 ± 0.69	5.9 ± 0.21	19.1 ± 0.62
	17	28.8 ± 0.57	6.4 ± 0.20	22.7 ± 0.59
	32	34.2 ± 0.73	7.2 ± 0.16	25.5 ± 0.88
	52	39.5 ± 1.2	7.9 ± 0.27	26.4 ± 0.94
	87	41.7 ± 1.1	8.2 ± 0.35	27.7 ± 1.1
Myriophyllum verticillatum	0	11.4 ± 0.43	6.7 ± 0.27	7.6 ± 0.29
	7	20.2 ± 0.75	13.5 ± 0.38	16.3 ± 0.47
	17	82.7 ± 3.3	27.3 ± 0.95	42.8 ± 1.6
	32	167 ± 6.6	41.6 ± 1.3	62.4 ± 1.9
	52	206 ± 7.9	47.8 ± 1.7	70.8 ± 2.6
	87	224 ± 9.2	53.9 ± 2.2	76.9 ± 2.5
Alternanthera philoxeroides	0	8.8 ± 0.27	5.2 ± 0.18	7.9 ± 0.28
	7	18.9 ± 0.52	6.4 ± 0.19	11.6 ± 0.33
	17	57.6 ± 2.1	11.1 ± 0.44	29.1 ± 0.96
	32	84.2 ± 2.9	17.8 ± 0.59	36.7 ± 0.89
	52	128 ± 3.6	20.6 ± 0.66	42.3 ± 1.4
	87	142 ± 5.4	24.6 ± 0.85	47.2 ± 1.7

2.2 Remediation Efficiency

The TN removal levels of five cultivars were shown in Fig. 2(a). Concentrations of TN by different kinds of cultivars decreased from 20.75 ± 2.5 to 3.03 ± 1.9 $\mathrm{mg \cdot L^{-1}}$ during the monitoring time. Statistical analysis revealed a significant variation ($P<0.05$) between the aqua-cultured plants and controls. The removal efficiency was found to be in the order of *Myriophyllum verticillatum* (96%)>*Chlorophytum comosum* (95%)>*Alternanthera philoxeroides* (82%)>*Dracaena sanderiana* (81%)>*Salix babylonica* (69%)>controls (12%).

Concentrations of TP (ranged from 14.03±1.1 to 2.5±1.8 $\mathrm{mg \cdot L^{-1}}$) decreased significantly in the eutrophic water with five aqua-cultured plants ($P<0.05$, Fig. 2(b)). The removal efficiencies of *Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, and *Alternanthera philoxeroides* were calculated to be 93%, 64%, 71%, 95%, and 86%, respectively. These values were approximately 5-7 times higher than the control without aqua-cultured plants.

The concentrations of $\mathrm{COD_{Cr}}$ purified by different kinds of cultivars were 18.20 ± 5.5 $\mathrm{mg \cdot L^{-1}}$ and 3.26 ± 3.07 $\mathrm{mg \cdot L^{-1}}$ at time 0 d and 87 d, respectively, showing a decreasing trend during the experimental period (Fig. 2(c)). The highest removal efficiency was induced by *Myriophyllum verticillatum* (96%), followed by *Alternanthera philoxeroides* (91%), *Chlorophytum comosum* (88%), *Dracaena sanderiana* (83%), *Salix babylonica* (44%), and the controls (15%).

At time phase 0 d and 87 d, the values of SD were in the range of 0.08 to 0.1 m and 1.3 to 3.2 m, respectively. The deepest treatments were 3.2 m (*Myriophyllum verticillatum*), followed by 2.8 m (*Alternanthera philoxeroides*), 2.4 m (*Chlorophytum comosum*), 1.9 m (*Dracaena sanderiana*), and 1.3 m (*Salix babylonica*), which were higher than the control by 2-6 folds (Fig. 2(d)).

The concentrations of *Chl-a* should be high because the TP concentrations were very high at the initial time. In fact, the initial concentrations of *Chl-a* were just 1.5-2.3 $\mathrm{\mu g \cdot L^{-1}}$ due to the fact that algae cannot quickly adapt the mixture environment with urban sewage. Time courses of concentrations of *Chl-a* for all treatments showed the same tendency as well as TN, TP, and $\mathrm{COD_{Cr}}$ (Fig. 2(e)). At the end of culture experiments, the concentrations of *Chl-a* decreased to 0.1-0.8 $\mathrm{\mu g \cdot L^{-1}}$. The purification efficiency of the five cultivars ranged from 47% to 96%, which were approximately 6-11 times higher than that of the control (8.5%). The best three treatmented plants were *Myriophyllum verticillatum* (95%), *Alternanthera philoxeroides* (87%), and *Chlorophytum comosum* (83%). The last one was *Salix babylonica* (47%).

Those results suggested that the five aqua-cultured plants we selected can significantly remove nutrients in Lake Hongfeng. Also, all the SD increased with the time for the treatments by cultivars. The best plant of remediation was *Myriophyllum verticillatum*, which can remove more than 93% of nutrients for all eutrophication indexes[23]. Moreover, *Alternanthera philoxeroides* and *Chlorophytum comosum* can also be applied to ecological remediation in karst drainage area in Guizhou Plateau because of their perfect remediation efficiency.

2.3 Evaluation

Modified Carlson's trophic state index (CTSI) was applied to evaluate the trophic state of Lake Hongfeng in the study site during experimental period[18, 21, 22]. CTSI requires the determination of five physic chemical variables, viz. *Chl-a*, TP, SD, TN, $\mathrm{COD_{Cr}}$.

The trophic state index (TSI) of Carlson was calculated using the following formulae.

TSI for *Chl-a* (CA) $\mathrm{TSI} = 10\times(2.5 + 1.086 \ln \mathit{Chl\text{-}a})$

TSI for TP $\mathrm{TSI} = 10\times(9.436 + 1.624 \ln \mathrm{TP})$

TSI for TN $\mathrm{TSI} = 10\times(5.453 + 1.694 \ln \mathrm{TN})$

TSI for SD $\mathrm{TSI} = 10\times(5.118 - 1.94 \ln \mathrm{SD})$

TSI for $\mathrm{COD_{Cr}}$ $\mathrm{TSI} = 10\times(0.019 + 2.66 \ln \mathrm{COD_{Cr}})$

$$\mathrm{CTSI} = \sum_{j=1}^{5} \frac{r_j^2}{\sum_{j=1}^{5} r_j^2} \mathrm{TSI}(j)$$

where r_j^2 is 1, 0.705 6, 0.672 4, 0.688 9, and 0.688 9 for *Chl-a*, TP, TN, SD, and $\mathrm{COD_{Cr}}$, and j =1, 2, 3, 4, 5, representing *Chl-a*, TP, TN, SD, or $\mathrm{COD_{Cr}}$, respectively[21,22,24]. The range of the Carlson's trophic state index values and classification of lakes are presented in Refs. [24-26].

Before the plants were cultured, the Carlson's trophic state indexes of the water within enclosure were calculated to be 69-76, and the trophic states were eutrophic (Fig. 3). Then the Carlson's trophic state index decreased significantly with time course of all treatments. The final Carlson's trophic state indexes were calculated to be 32.55±1.54, 52.88±2.60, 39.70±2.98, 20.73±1.71, 27.32±1.11, and 58.47±4.3 for the treatments with *Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, *Alternanthera philoxeroides*, and the controls, respectively. The trophic states were evaluated to be oligotrophic, eutrophic, oligotrophic, oligotrophic, oligotrophic, and eutrophic for each treatment. These results suggested that *Myriophyllum verticillatum* can be selected as the plant to remediate the karst drainage area of Guizhou Plateau.

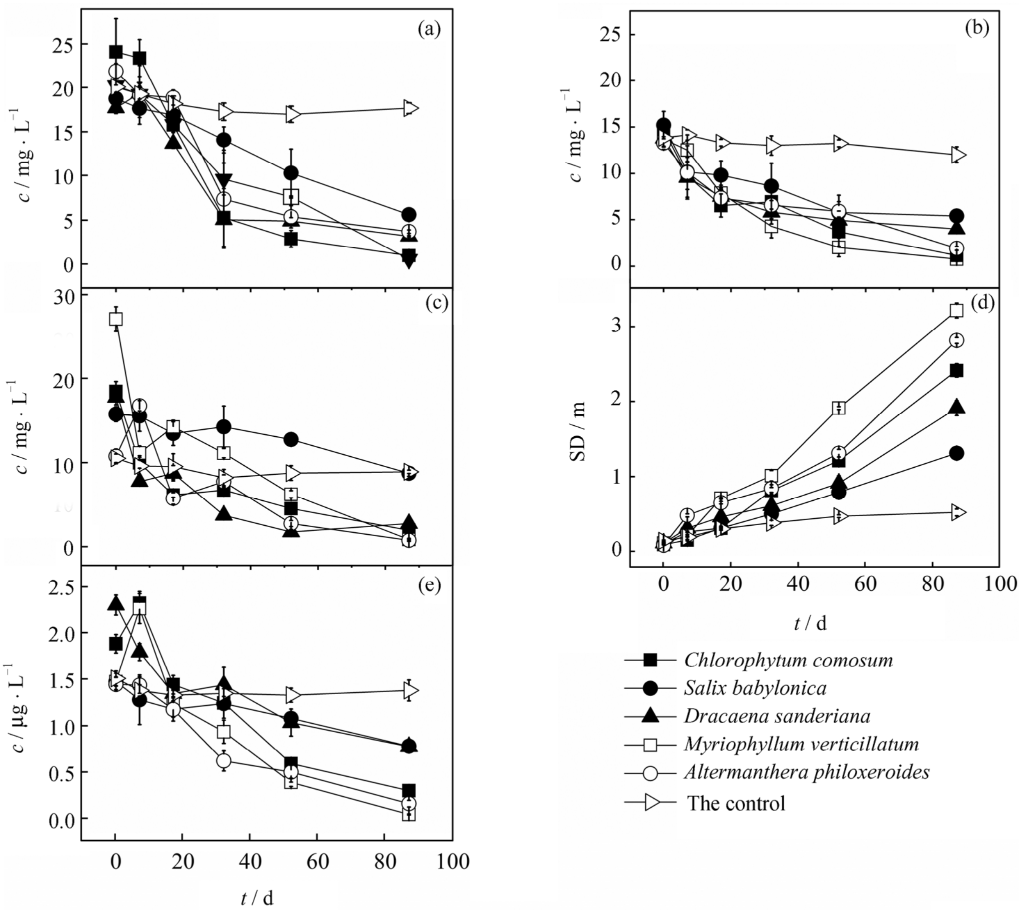

Fig. 2 Profiles of TN (a), TP (b), COD_{cr} (c), SD (d), and *Chl-a* (e)

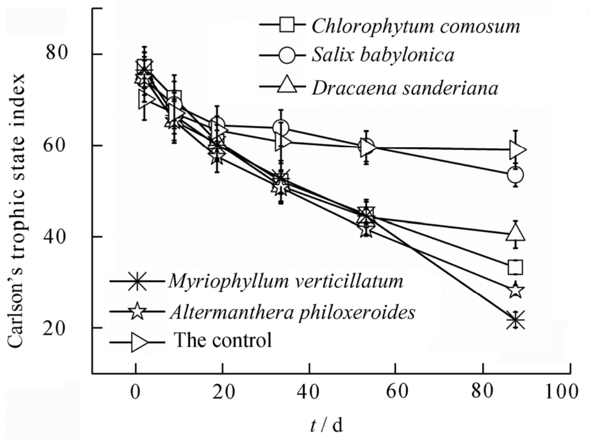

Fig. 3 Profiles of Carlson's trophic state index

3 Discussion

3.1 Relationship between Growth Characteristics and Purification Efficiency of Eutrophic Water

The results presented above indicated that the removal efficiency of eutrophic water was perfect when the biomass production were high and vice versa. Correlation analysis revealed that purification efficiency of eutrophic water correlated significantly, in a positive way, with the biomass amount and plant productivity (Table 2), suggesting that the efficiency of removing nutrients by aqua-cultured plants depended upon the pro-

Table 2 Correlation (R^2) between growth characteristics and purification efficiency of eutrophic water

Growth index	TN	TP	COD_{Cr}	*Chl-a*	SD	TSI
Fresh weight	0.820	0.820	0.729	0.925*	0.807	0.922*
Root length	0.824	0.824	0.616	0.827	0.626	0.832
Plant height	0.771	0.771	0.665	0.873	0.724	0.884*

* means correlation is significant at the 0.05 level (2-tailed)

duction of plant biomass, since aqua-cultured plants must grow with large amounts of nutrients. So the higher the biomass production, the more nutrients they can remove. In addition, longer roots can create more favorable conditions for microbial decomposition of organic matter. Therefore, the purification efficiency positively correlated with the biomass production of cultivars.

3.2 Comparison of Purification Efficiency

There are many factors such as temperatures, light conditions, types of cultivars, purification times, water velocity, physicochemical characteristics of water, plant biomass production, and so on, which can influence the purification efficiency of eutrophic water. So even using the same kinds of plant may also make a great difference. There was a wide range of purification efficiency of nutrients by different bed vegetation as shown in Table 3. The removal efficiencies of our results were higher than those in published results. This is mainly because the enclosure is an independent ecosystem, which can prevent the supply of nutrients for cultivated plants. In addition, the experiment was conducted within an enclosure, so the water was stagnant and there was no external input of nutrients. Our results were thus more reliable than those in previous studies.

Table 3 Purification efficiency of ecological floating bed reported in published literatures

Time	Site	Cultivar	Item	Original concentration /mg·L^{-1}	Water temperature /℃	Experiment duration /d	Purification efficiency /%	Literature
July and August	Songjiang, Shanghai, China	Water spinach (*Ipomoea aquatica* Forsskal)	TN	3.0	24.9-33.3	56	11.2	Ref. [16]
			NH_4^+-N	1.24			60.0	
			NO_2^--N	0.6			60.2	
			TP	0.27			27.3	
—	Laboratory*	Italian ryegrass (*L. multiflorum* L.)	NO_3^-	50-150	22	10	90.3-96.1	Ref. [27]
May to August, 2007	Meiliang Bay, Lake Taihu, Jiangsu, China	*Ipomoea aquatica*	NH_4^+-N	3.6	—	7	33.7	Ref. [28]
			TN	3.7			52.7	
			TP	0.66			54.5	
			TOC	12.3			49.2	
			Chl-a	3.8			80.2	
Winter-spring season	Jiaxing, Zhejiang, China	*Eichhirnia crasslpes*, *Pisitia stratiotes*, *Jussiaea reppens*, *Hydrocotyle verticillata*, *Hydrocharis dubia*, *Myriophyllum aquaticum*, *Pontederia cordata*, *Canna indica*, *Calla palustris*	TN	7.8	30	150	36.9	Ref. [15]
			NH_4^+-N	8.0			44.8	
			NO_3^--N	4.1			25.6	
			NO_2^--N	0.38			53.2	
			TP	0.35			43.3	
			Chl-a	0.0835			64.5	
June to August, 2017	Lake Hongfeng, Guizhou, China	*Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*	TN	20.75	21.8-27.5	87	69-96	This study
			TP	14.03			64-95	
			COD_{Cr}	18.20			44-96	
			Chl-a	0.001 5-0.002 3			47-95	

*Controlled climatic conditions (laboratory simulation experiments)

4 Conclusion

The purification efficiency of eutrophic water by five plants cultivated in floating beds increased with the extension of experimental period. The removal efficiencies of TN, TP, COD_{Cr}, *Chl-a* were 69%-96%, 64%-95%, 44%-96%, and 47%-95% for *Chlorophytum comosum*, *Salix babylonica*, *Dracaena sanderiana*, *Myriophyllum verticillatum*, *Alternanthera philoxeroides*, respectively. The SD increased from 0.08-0.1 m to 1.3-3.2 m in the experiments treated by the five plants. Purification efficiency of eutrophic water had a significant positive correlation with the biomass amount and plant productivity. The biomass amount and plant productivity of *Myriophyllum verticillatum* were the largest in this study, so the *Myriophyllum verticillatum* was the best plant for rapid removal of nutrients from eutrophic water in the karst drainage area of Guizhou Plateau.

References

[1] Akçaalan R, Köker L, Albay M. Do eutrophic waters prompt to toxic cyanobacteria in Turkish Black Sea coast? [J]. *Journal of Environmental Protection and Ecology*, 2016, **17**(5): 584-592.

[2] Cao W, Zhang Y. Removal of nitrogen (N) from hypereutrophic waters by ecological floating beds (EFBs) with various substrates [J]. *Ecological Engineering*, 2014, **62**(1): 148-152.

[3] Chang N B, Wanielista M P, Xuan Z, *et al*. Floating treatment wetlands for nutrient removal in a subtropical stormwater wet detention pond with a fountain [J]. *Developments in Environmental Modelling*, 2014, **26**(12): 437- 467.

[4] Tudor I, Deak G, Tudor M. Zooplankton distribution and dynamics in a Gorgova-Uzlina, Sontea-Furtuna, Rosu-Puiu and Matita-Merhei complex of lakes from the Danube Delta-Romania [J]. *Journal of Environmental Protection and Ecology*, 2015, **16**(2): 434-442.

[5] Yan W, Liu L, Yu Z, *et al*. Nitrogen and phosphorus removal from eutrophic water by oxygen-enriched and combined ecological floating bed grown [J]. *Journal of Environmental Protection and Ecology*, 2013, **14**(4): 1542-1550.

[6] Zhao F, Yang W, Zeng Z, *et al*. Nutrient removal efficiency and biomass production of different bioenergy plants in hypereutrophic water [J]. *Biomass and Bioenergy*, 2012, **42**(7) : 212-218.

[7] Fu J. Issue of cyanobacteria blooms in Taihu Lake, China [J]. *Journal of Environmental Science and Management*, 2016, 19(2): 99-109(Ch).

[8] Wang J F, Chen J G, Ding S, *et al*. Effects of seasonal hypoxia on the release of phosphorus from sediments in deep-water ecosystem: A case study in Hongfeng Reservoir, Southwest China [J]. *Environmental Pollution*, 2016, **219**(2): 858-865.

[9] Wang J F, Chen J G, Dallimore C, *et al*. Spatial distribution, fractions, and potential release of sediment phosphorus in the Hongfeng Reservoir, southwest China [J]. *Lake and Reservoir Management*, 2015, **31**(3): 214-224.

[10] Li M, Wu Y J, Yu Z L, *et al*. Nitrogen removal from eutrophic water by floating-bed-grown water spinach (*Ipomoea aquatica* Forsk.) with ion implantation [J]. *Water Research*, 2007, **41**(14): 3152-3158.

[11] Hu G J, Zhou M, Hou H B, *et al*. An ecological floating-bed made from dredged lake sludge for purification of eutrophic water [J]. *Ecological Engineering*, 2010, **36**(10): 1448-1458.

[12] Cao W, Wang Y, Sun L, *et al*. Removal of nitrogenous compounds from polluted river water by floating constructed wetlands using rice straw and ceramsite as substrates under low temperature conditions [J]. *Ecological Engineering*, 2016, **88**(3): 77-81.

[13] Chang N B, Lin K S, Wanielista M P, *et al*. An innovative solar energy-powered floating media bed reactor for nutrient removal (Ⅰ): Reactor design [J]. *Journal of Cleaner Production*, 2016, **133**(5): 495-503.

[14] Liu J, Wang F, Liu W, *et al*. Nutrient removal by up-scaling a hybrid floating treatment bed (HFTB) using plant and periphyton: From laboratory tank to polluted river [J]. *Bioresource Technology*, 2016, **207**(9): 142-149.

[15] Zhao F, Xi S, Yang X, *et al*. Purifying eutrophic river waters with integrated floating island systems [J]. *Ecological Engineering*, 2012, **40**(3): 53-60.

[16] Zhang Q, Achal V. Aquaculture wastewater quality improvement by water spinach (*Ipomoea aquatica* Forsskal) floating bed and ecological benefit assessment in ecological agriculture district [J]. *Aquacultural Engineering*, 2014, **60**(3): 48-55.

[17] Ge Z, Feng C, Wang X, *et al*. Seasonal applicability of three vegetation constructed floating treatment wetlands for nutrient removal and harvesting strategy in urban stormwater retention ponds [J]. *International Biodeterioration & Biodegradation*, 2016, **112**(8): 80-87.

[18] Smith S D. The roles of nitrogen and phosphorus in regulating the dominance of floating and submerged aquatic plants in a field mesocosm experiment [J]. *Aquatic Botany*, 2014, **112**(112): 1-9.

[19] Environmental Protection Department. *Environmental Quality Standard for Surface Water* (GB3838-2002)[S]. Beijing: China Environmental Science Press, 2002(Ch).

[20] Pu P M, Li Y H, Zhang J F, *et al*. Eutrophication control in local area through phytoplankton population regulation by eco-remediation: A case study on aqua-eco-remediation engineering in Lake Hongfeng, Guizhou Province [J]. *Journal of Lake Science*, 2012, **24**(4): 503-512(Ch).

[21] Wang G, Zhang L, Chua H, *et al*. A mosaic community of macrophytes for the ecological remediation of eutrophic shallow lakes [J]. *Ecological Engineering*, 2009, **35**(4): 582-590.

[22] State Environmental Protection Administration editorial committee. *Water and Wastewater Monitoring Method* [M]. 4th Edition. Beijing: Environmental Science Press, 2002 (Ch).

[23] Wu R, Gui L F, Jiang L W, *et al*. The effects of ceratophyllum and myriophyllum on the production and release of cyanotoxins in *Microcystis aeruginosa* [J]. *Journal of Hydroecology*, 2010, **3**(3): 43-46(Ch).

[24] Jin X, Tu Q. *Survey Standards of Lake Eutrophication* [M]. 2nd Edition. Beijing: Science China Press, 1990(Ch).

[25] Jin X, liu S, Zhang Z. *Chinese Lake Environmental* [M]. Beijing: The Ocean Publishing Company, 1995(Ch).

[26] Devi Prasad A G. Carlson's trophic state index for the assessment of trophic status of two lakes in Mandya district [J]. *Advances in Applied Science Research*, 2012, **3**(5): 2992-2996.

[27] Bartucca M L, Mimmo T, Cesco S, *et al*. Nitrate removal from polluted water by using a vegetated floating system [J]. *Science of the Total Environment*, 2016, **542**(Pt A): 803-808.

[28] Xian N L, Song H L, Li W, *et al*. An integrated ecological floating-bed employing plant, freshwater clam and biofilm carrier for purification of eutrophic water [J]. *Ecological Engineering*, 2010, **36**(4): 382-390.

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